



FERMILAB-Pub-77/44-EXP  
7100.180

(Submitted to Phys. Rev. Lett.)

## SCALING VARIABLE DISTRIBUTIONS FOR ANTINEUTRINO-NUCLEON INTERACTIONS

J. P. Berge, D. Bogert, F. A. DiBianca, H. Emans, R. Endorf,  
R. Hanft, C. Kochowski, J. Malko, F. A. Nezrick, W. G. Scott,  
W. Smart, W. Venus, and J. Wolfson  
Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA

and

V. V. Ammosov, A. G. Denisov, P. F. Ermolov, V. A. Gapienko,  
V. I. Klujkin, V. I. Koreshev, A. I. Mukhin, P. V. Pitukhin,  
Y. G. Rjabov, E. A. Slobodyuk, and V. I. Sirotenko  
Institute of High Energy Physics, Serpukhov, USSR

and

V. I. Efremenko, P. A. Gorichev, V. S. Kaftanov, V. D. Khovansky,  
G. K. Kliger, V. Z. Kolganov, S. P. Kruchinin,  
M. A. Kubantsev, A. N. Rosanov, and V. G. Shevchenko  
Institute of Theoretical and Experimental Physics, Moscow, USSR

and

C. T. Coffin, R. N. Diamond, H. French, W. Louis, B. P. Roe,  
R. T. Ross, A. A. Seidl, and D. Sinclair  
University of Michigan, Ann Arbor, Michigan 48104 USA

May 1977



SCALING VARIABLE DISTRIBUTIONS FOR  
ANTINEUTRINO-NUCLEON INTERACTIONS

J. P. Berge, D. Bogert, F. A. DiBianca, H. Emans,<sup>+</sup> R. Endorf,<sup>‡</sup>  
R. Hanft, C. Kochowski,\* J. Malko, F. A. Nezrick, W. G. Scott,  
W. Smart, W. Venus,<sup>‡</sup> and J. Wolfson  
Fermi National Accelerator Laboratory,  
Batavia, Illinois 60510, USA

and

V. V. Ammosov, A. G. Denisov, P. F. Ermolov, V. A. Gapienko,  
V. I. Klujkin, V. I. Koreshev, A. I. Mukhin, P. V. Pitukhin,  
Y. G. Rjabov, E. A. Slobodyuk, and V. I. Sirotenko  
Institute of High Energy Physics  
Serpuukhov, USSR

and

V. I. Efremenko, P. A. Gorichev, V. S. Kaftanov, V. D. Khovansky,  
G. K. Kliger, V. Z. Kolganov, S. P. Kruchinin,  
M. A. Kubantsev, A. N. Rosanov, and V. G. Shevchenko  
Institute of Theoretical and Experimental Physics,  
Moscow, USSR

and

C. T. Coffin, R. N. Diamond,<sup>§</sup> H. French, W. Louis, B. P. Roe,  
R. T. Ross, A. A. Seidl, and D. Sinclair  
University of Michigan  
Ann Arbor, Michigan 48104 USA

---

<sup>+</sup>Visitor from the University of Bonn, Bonn, Germany.

<sup>‡</sup>Visitor from the University of Cincinnati, Cincinnati, Ohio.

\*Visitor from the Centre d' Etudes Nucleaires de Saclay,  
Saclay, France.

<sup>‡</sup>Visitor from the Rutherford High Energy Laboratory,  
Chilton, Didcot, Berkshire, England.

<sup>§</sup>Present address: Florida State University, Tallahassee, Florida.

# ABSTRACT

New data are reported on high energy antineutrino interactions obtained using the Fermilab 15-Ft. bubble chamber filled with a light neon-hydrogen mixture. The new data support a gentle energy dependence for the  $y$ -distribution consistent with the trend of the existing data, but show no evidence for a marked energy threshold. The data for  $\langle x \rangle$  and the data for  $\langle \nu \rangle = \langle xy \rangle$  show some decrease with increasing energy which may be related to scaling deviations measured in electron and muon experiments.

In experiments using calorimeter - spectrometer techniques evidence has been reported for a sudden change in character of the antineutrino muon inelasticity distributions at high energies.<sup>1, 2</sup> These data have been extensively discussed in the theoretical literature and have been considered as evidence for new particle production, right-handed currents and/or asymptotic-freedom effects.<sup>3, 4</sup> Interest centers on the behavior at high- $y$ <sup>5</sup> where in experiments using calorimeter-spectrometer techniques, muon acceptance losses have been particularly large. In this letter we report the results of an experiment on high energy charged current antineutrino scattering performed using the Fermilab 15-Ft. bubble chamber. Used in conjunction with the External Muon Identifier (EMI)<sup>6</sup> the bubble chamber has the important advantage of good muon angular acceptance out to relatively high values of  $y$ .

The data come from 60,000 pictures obtained using a 21% atomic neon-hydrogen filling of the bubble chamber exposed to a broad-band double horn focused antineutrino beam. The energy of the extracted proton beam was 300 GeV and the proton intensity on the target was  $0.8-0.9 \times 10^{13}$  protons per pulse. The EMI consisted of between 3 and 5 interaction lengths of hadron absorber followed by an array of multiwire proportional chambers with a total area of  $23 \text{ m}^2$ . The data from the proportional chambers for each picture taken were written to magnetic tape by an on-line computer which was also used to monitor the performance of the EMI throughout the exposure.

The film was scanned for events with total momentum along the beam direction  $p_x$  greater than about 1 GeV. Not included in the scan were events consisting of a single charged track only (1-prong events) which include candidates for the elastic reaction  $\bar{\nu}_\mu p \rightarrow \mu^+ n$ . In order to remove the effect of the bias due to the loss of 1-prong events, all events with hadronic energy  $\nu < 2$  GeV are eliminated from the sample.<sup>5</sup> The data have been corrected for scanning losses. The scan efficiency was measured in a partial double scan and the data were corrected by weighting the events as a function of the total multiplicity. For events with  $\nu > 2$  GeV the scan efficiency as a function of  $y$  varies from 0.90 to 0.98 and is largest for events at high- $y$ .

In order to identify muons in these events, all tracks leaving the bubble chamber without interacting are extrapolated to the EMI plane in an attempt to match them with fitted coordinates from the proportional chambers. For this analysis tracks which match in the EMI and have a muon confidence level greater than 4% and a hadron confidence level less than 10% are taken as identified muons.<sup>6</sup> Only events with a positive muon identified by the EMI are included in the charged current sample. To reduce backgrounds in the sample due to events where a positive hadron is misidentified as a muon by the EMI and also to ensure good EMI acceptance we require that the total measured momentum of the event along the beam direction be greater than 7.5 GeV/c and that the momentum of the muon be greater than 4 GeV/c.<sup>7</sup> The events have been weighted to correct for the

geometrical acceptance of the EMI. Figure 1 shows the EMI acceptance for positive muons computed for the fiducial volume used in this experiment, as a function of the muon momentum ( $p^\mu$ ) and angle ( $\theta^\mu$ ). For forward muons ( $\theta^\mu \sim 0$ ) the EMI acceptance is  $\sim 0.96$  falling to  $\sim 0.60$  for  $\theta^\mu = 0.5$  rad. At fixed angle the EMI acceptance is not strongly dependent on muon momentum for  $p^\mu > 4$  GeV/c. In terms of the variables  $x$  and  $y$  the effect of the requirement on the muon momentum ( $p^\mu > 4$  GeV/c) together with the requirement on the hadron energy ( $\nu > 2$  GeV) is that, the data are confined to a restricted range in  $y$  defined by  $y_{\min} < y < y_{\max}$  where  $y_{\min} = 2/E$  and  $y_{\max} = 1-4/E$  (with  $E$  in GeV). Within this  $y$ -range the data cover the full kinematic range in  $x$  ( $x = 0-1$ ).

The energy of the incident antineutrino is estimated by summing the momentum of the muon and the momentum of the hadrons along the beam direction. The momentum of the hadrons has to be corrected to account for neutrals which leave the chamber undetected. In an experiment using a complex nuclear target we do not expect to see momentum balance in individual events due to the presence of undetected nuclear fragments. However the mean transverse momentum of the hadrons  $\langle p_T^h \rangle$  and the mean transverse momentum of the muon  $\langle p_T^\mu \rangle$ , measured relative to the antineutrino direction in the plane defined by the muon and the antineutrino, are expected to balance if there is no other source of missing momentum. The correction factor for missing

momentum  $\langle p_T^u \rangle / \langle p_T^h \rangle$  is evaluated as a function of the longitudinal momentum of the visible hadrons  $p_x^h$ . A straight line fit to the mean corrected value of  $p_x^h$ ,  $p_x^h$  (corrected) as a function of  $p_x^h$  gives:  $p_x^h$  (corrected) = 1.20 ( $p_x^h + 1.0$  GeV). All events are corrected for missing hadron momentum using this formula.<sup>8</sup>

Assuming the validity of the Callan-Gross relation<sup>9</sup> the differential cross section in  $y$  for charged current antineutrino scattering integrated over any range of  $x$  is given in terms of the structure functions  $F_2$  and  $xF_3$ .

$$\frac{d\sigma}{dy} = \frac{G^2 mE}{\pi} \left[ \left(1-y + \frac{y^2}{2}\right) \int F_2 dx - y \left(1 - \frac{y}{2}\right) \int xF_3 dx \right] \quad (1a)$$

or

$$\frac{d\sigma}{dy} = \frac{G^2 mE}{\pi} \int F_2 dx \left[ \left(1-y + \frac{y^2}{2}\right) - By \left(1 - \frac{y}{2}\right) \right] \quad (1b)$$

where  $B = \int xF_3 dx / \int F_2 dx$ . In the quark parton model the value of  $B$  is related to the relative antiquark content of the nucleon by the relation:

$$\frac{\bar{Q}}{Q + \bar{Q}} = \frac{1 - B}{2} \quad (2)$$

where  $Q$  and  $\bar{Q}$  represent the relative contribution of quarks and antiquarks for the same  $x$ -range. If the antiquark contribution

can be neglected then  $B = 1$  and the  $y$ -distribution has a pure  $(1 - y)^2$  form. In the quark parton model a measurement of the  $y$ -distribution determines the relative antiquark contribution.

Figures 2a-2c show the  $y$ -distributions for the energy intervals 10-30, 30-50 and 50-200 GeV. The distributions are inconsistent with a pure  $(1-y)^2$  form but are well fitted by the form 2b. The curve shows the best fit for each energy interval. Figures 2d-2f show the  $x$ -distributions for restricted regions of  $y$  for the same energy intervals. In each case the curve which has been normalized to the data is a prediction computed from the quark distributions of Field and Feynman<sup>10</sup> which are based on electron data and neutrino/antineutrino data from experiments at lower energies.

Table I shows the fitted value of  $B$  from the  $y$ -distributions for various ranges of  $x$  for the three energy intervals. While there is no statistically significant energy dependence the trend of the data suggest that the effective antiquark contribution at small  $x$  is increasing with increasing energy. Fig. 3a shows the relative antiquark contribution  $\bar{Q}/(Q + \bar{Q})$  as a function of  $x$  computed using all the data in the energy range 10-200 GeV. The curve is from Field and Feynman. For the whole  $x$ -range the data give  $\bar{Q}/(Q + \bar{Q}) = 0.14 \pm 0.03$  while the prediction from Field and Feynman is 0.08. At these energies, the effective antiquark contribution is larger and extends to higher values of  $x$  than would be expected based on the lower energy data.

Figure 3b shows the value of B for the maximum x-range plotted as a function of energy. Also shown in Fig. 3b are the data from the Harvard-Pennsylvania-Wisconsin-Fermilab (HPWF) collaboration<sup>1</sup> and the data from the Caltech-Fermilab (CTF) collaboration.<sup>2</sup> The lowest energy point comes from a fit<sup>13</sup> to the antineutrino y-distribution for the subset of events in the scaling region in the Gargamelle (GGM) experiment. Taken together with the data from the other experiments our data support a gentle energy dependence for B. The combined world data for B are very well fit ( $\chi^2 = 3.86$  for 6 DF) by a linear energy dependence and the best fit gives:

$$B = (0.86 \pm 0.05) - (0.0038 \pm 0.0012)E \quad (3)$$

The evidence for a sudden change in the shape of the y-distribution with energy comes from the data published by the HPWF collaboration. The determination of B in this experiment for the energy range 10-30 GeV is two standard-deviations lower than the HPWF determination of B in the same energy range.

Figure 4a shows the mean value of y as a function of energy for  $y = 0.2-0.6$  for  $E > 10$  GeV and for  $y = 0.05-0.9$  for  $E > 40$  GeV. The curves show the expected energy dependences computed from Eq. 3 for the two y-intervals. While it is difficult to make a direct comparison with the data for  $\langle y \rangle$  from the HPWF collaboration which are plotted for an energy dependent y-range, our data show no evidence for a sharp rise in  $\langle y \rangle$  in the

vicinity of 30 GeV.<sup>1</sup> Our data for  $\langle y \rangle$  are compatible with the energy dependence predicted from Eq. 3.

Deviations from exact Bjorken scaling have been observed in electron/muon experiments.<sup>14</sup> In neutrino/antineutrino experiments similar effects would appear as a decrease in the mean value of  $x$  as a function of energy. On the basis of empirical fits<sup>15</sup> to electron/muon data we predict  $\langle x \rangle \propto E^{-b}$  with  $b \sim 0.15$ . Figure 4b shows the data for  $\langle x \rangle$  plotted in fine energy intervals. The best fit to the data for  $y = 0.2-0.6$  over the whole energy range gives  $b = 0.14 \pm 0.06$  ( $\chi^2 = 14.0$  for 10 DF). While the evidence for scaling deviations in this experiment is marginal statistically, the observed energy dependence is compatible with expectations based on electron and muon data. Figure 4c shows the energy dependence of the mean value of  $v$  ( $v = xy$ ) for the same restricted  $y$ -ranges. In the approximation that the  $x$  and  $y$  dependence factorize we expect a similar energy dependence for  $\langle v \rangle$ . The best fit to the form  $\langle v \rangle \propto E^{-b}$  for  $y = 0.2-0.6$  over the whole energy range gives  $b = 0.09 \pm 0.09$  ( $\chi^2 = 8.8$  for 10 DF). In Fig. 4b-4c the curves are fits to the data in the two  $y$ -ranges assuming  $b = 0.15$ . For  $y = 0.05 - 0.9$  and  $E > 40$  GeV the data for  $\langle v \rangle$  show a more rapid fall-off with increasing energy than is indicated by the fit. For this  $y$ -range the data give  $\langle v \rangle = 0.086 \pm 0.010$  for  $E = 40-60$  GeV and  $\langle v \rangle = 0.048 \pm 0.007$  for  $E = 60-200$  GeV.

In summary we conclude that the  $y$ -distribution for charged current antineutrino scattering is inconsistent with a pure  $(1-y)^2$  form over the energy range explored in this experiment.

In terms of the quark parton model the relative antiquark contribution is larger than would be expected based on the low energy data and extends to larger values of  $x$ . When combined with the world data our data support a gentle energy dependence for the  $y$ -distribution which can be parameterized by a linear energy dependence  $B = (0.86 \pm 0.05) - (0.0038 \pm 0.0012)E$  over the energy range  $4 < E < 150$  GeV. While the  $x$ -distributions are in reasonable agreement with predictions based on the quark-parton model and electron scattering data, the data for  $\langle x \rangle$  and the data for  $\langle v \rangle$  as functions of energy show a decrease with increasing energy. The observed energy dependence may be related to similar scaling deviations measured in electron and muon scattering experiments.

We wish to thank the Hawaii and Berkeley groups for their assistance in operating the EMI and for making available to us their EMI programs. We also wish to thank the members of the Neutrino Laboratory at Fermilab and the scanning, measuring and secretarial staffs at our respective laboratories for their contribution to this experiment.

REFERENCES

- <sup>1</sup>A. Benvenuti, et al., Phys. Rev. Lett. 36, 1478 (1976).
- <sup>2</sup>B. C. Barish, et al., Phys. Rev. Lett. 38, 314 (1976).
- <sup>3</sup>R. M. Barnett, Phys. Rev. Lett. 36, 1163 (1976) and Phys. Rev. D14 70 (1976): S. Pakuasa, L. Pilachowski, W. A. Simmons and S. F. Tuan, Nucl. Phys. B109 469 (1976): V. Barger, T. Weiler and R. J. N. Phillips, Phys. Rev. D14 1276 (1976); J. Kaplan and F. Martin, Nucl. Phys B115, 333 (1976); C. H. Albright and R. E. Shrock, Fermilab-PUB-77/19 THY (submitted to Phys. Rev.)
- <sup>4</sup>E. Altarelli, R. Petronzio and G. Parisi, Phys. Lett. 63B 183 (1976). R. M. Barnett, H. Giorgi and H. D. Politzer, Phys. Rev. Lett. 37, 1313 (1976).
- <sup>5</sup>The scaling variables are defined by  $x = Q^2/2mv$  and  $y = v/E$  where  $Q^2$  is the square of the 4-momentum transfer,  $v$  is the energy transfer to the hadrons in the lab and  $E$  is the energy of the incoming antineutrino.
- <sup>6</sup>R. J. Cence, Nucl. Instr. and Meth. 138, 245 (1976).
- <sup>7</sup>The remaining background in the final charged current sample is estimated to have a negligible effect on the distributions.
- <sup>8</sup>See for example: F. A. Nezrick invited talk given at the SLAC Summer Institute on Particle Phys. October (1976). Fermilab PUB-76/90-EXP 7100.180. Systematic errors from the energy correction procedure have been investigated and are unimportant compared to statistical errors.
- <sup>9</sup>C. G. Callan and D. J. Gross, Phys. Rev. Lett. 22, 156 (1969). Modifications of the Callan-Gross relation are expected if heavy quark production plays an important role at these ener-

gies (C. H. Albright and R. E. Shrock, Ref. 3). The quantity  $B$  defined by Eq. 1a and 1b should be regarded as an empirical fitting parameter used to describe the shape of the measured  $y$ -distributions.

<sup>10</sup>R. D. Field and R. P. Feynman, Caltech Preprint CALT-68-565.

<sup>11</sup>H. Deden, et al., Nuclear Physics B85, 269 (1975).

<sup>12</sup>The data from this experiment covers the full  $x$ -range  $x=0-1$ .

The data from the other experiments are plotted for the maximum accessible  $x$ -range in each case. e.g.,  $x < 0.6$  for the HPWF data and  $x < 0.4$  for the GGM data. Since the  $x$ -distribution falls off very rapidly with increasing  $x$  the effect of the different cuts in  $x$  is not expected to be important.

<sup>13</sup>D. H. Perkins, Proceedings of the Symposium on Lepton-Photon Interactions, SLAC (1975).

<sup>14</sup>Y. Watanabe, et al., Phys. Rev. Lett. 35, 898 (1975).

E. M. Riordan, et al., SLAC-PUB-1634 (1975).

H. L. Anderson, et al., Phys. Rev. Lett. 37, 4 (1976).

<sup>15</sup>D. H. Perkins, P. Schreiner, and W. G. Scott. CERN preprint CERN/EP/Phys 77 and ANL preprint ANL-HEP-PR-77-16 (1977) (submitted to Phys. Lett.). Empirical fits to measured scaling deviations in electron and muon scattering experiments yield the result  $\partial \ln F_2^{e,\mu N} / \partial \ln Q^2 = .25-x$  (where  $F_2^{e,\mu N}$  is the structure function for inelastic electron/muon scattering).

Assuming all three structure functions for antineutrinos show a similar  $Q^2$ -dependence, we predict  $\langle x \rangle \propto E^{-b}$  with  $b \sim \langle x \rangle - \langle x^2 \rangle / \langle x \rangle = 0.15 \pm 0.01$  in this experiment.

Table I: Fitted values of B as  
various x-range

| E GeV  | x-                       |                         |                         |                           |                         |
|--------|--------------------------|-------------------------|-------------------------|---------------------------|-------------------------|
|        | 0 - 0.1                  | 0.1 - 0.2               | 0.2 - 0.4               | 0.4 - 1.0                 | 0 - 1.0                 |
| 10-30  | 0.56 $^{+0.18}_{-0.24}$  | 0.90 $^{+0.08}_{-0.12}$ | 0.72 $^{+0.12}_{-0.18}$ | 0.88 $^{+0.10}_{-0.12}$   | 0.78 $^{+0.06}_{-0.08}$ |
| 30-50  | 0.32 $^{+0.30}_{-0.50}$  | 0.68 $^{+0.20}_{-0.34}$ | 0.76 $^{+0.13}_{-0.22}$ | 1.00 $^{+0.00}_{-0.10}$   | 0.70 $^{+0.10}_{-0.13}$ |
| 50-200 | -0.50 $^{+0.81}_{-2.38}$ | 0.52 $^{+0.32}_{-0.66}$ | 0.76 $^{+0.17}_{-0.34}$ | 1.00 $^{+0.00}_{-0.08}$   | 0.62 $^{+0.14}_{-0.20}$ |
| 10-200 | 0.38 $^{+0.17}_{-0.21}$  | 0.80 $^{+0.09}_{-0.11}$ | 0.74 $^{+0.09}_{-0.12}$ | 0.96 $^{+0.004}_{-0.008}$ | 0.73 $^{+0.05}_{-0.06}$ |

FIGURE CAPTIONS

- Figure 1: The geometrical acceptance of the EMI for positive muons as a function of the muon momentum  $p^\mu$  and muon angle  $\theta^\mu$ .
- Figure 2: a), b), and c). The y-distributions for the antineutrino energy ranges 10-30 GeV, 30-50 GeV and 50-200 GeV respectively. The curve is computed from the best fit for B in each case. d), e), and f). The x-distributions for the same energy ranges. The curve is a prediction computed from the quark distributions of Field and Feynman (Ref.10).
- Figure 3: a) The relative antiquark contribution  $\bar{Q}/(Q + \bar{Q})$  as a function of x computed using all the data in the energy range 10-200 GeV. The curve is computed from the quark distributions of Field and Feynman (Ref. 10). b) The world data for B for the maximum x-range plotted as a function of energy. The straight line is a linear fit to the total world data.
- Figure 4: a) The data for  $\langle y \rangle$  as a function of energy. The curves are computed from Eq. 3 for the two y-ranges. b) The data for  $\langle x \rangle$  as a function of energy.

The solid curve is  $\langle x \rangle \propto E^{-b}$  with  $b = 0.15$  (see text) fitted to the data for  $y = 0.2-0.6$ ,  $E > 10$  GeV. The broken curve is for  $y = 0.05-0.9$ ,  $E > 40$  GeV. c) The data for  $\langle v \rangle$  as a function of energy. The curves are for  $b = 0.15$  .

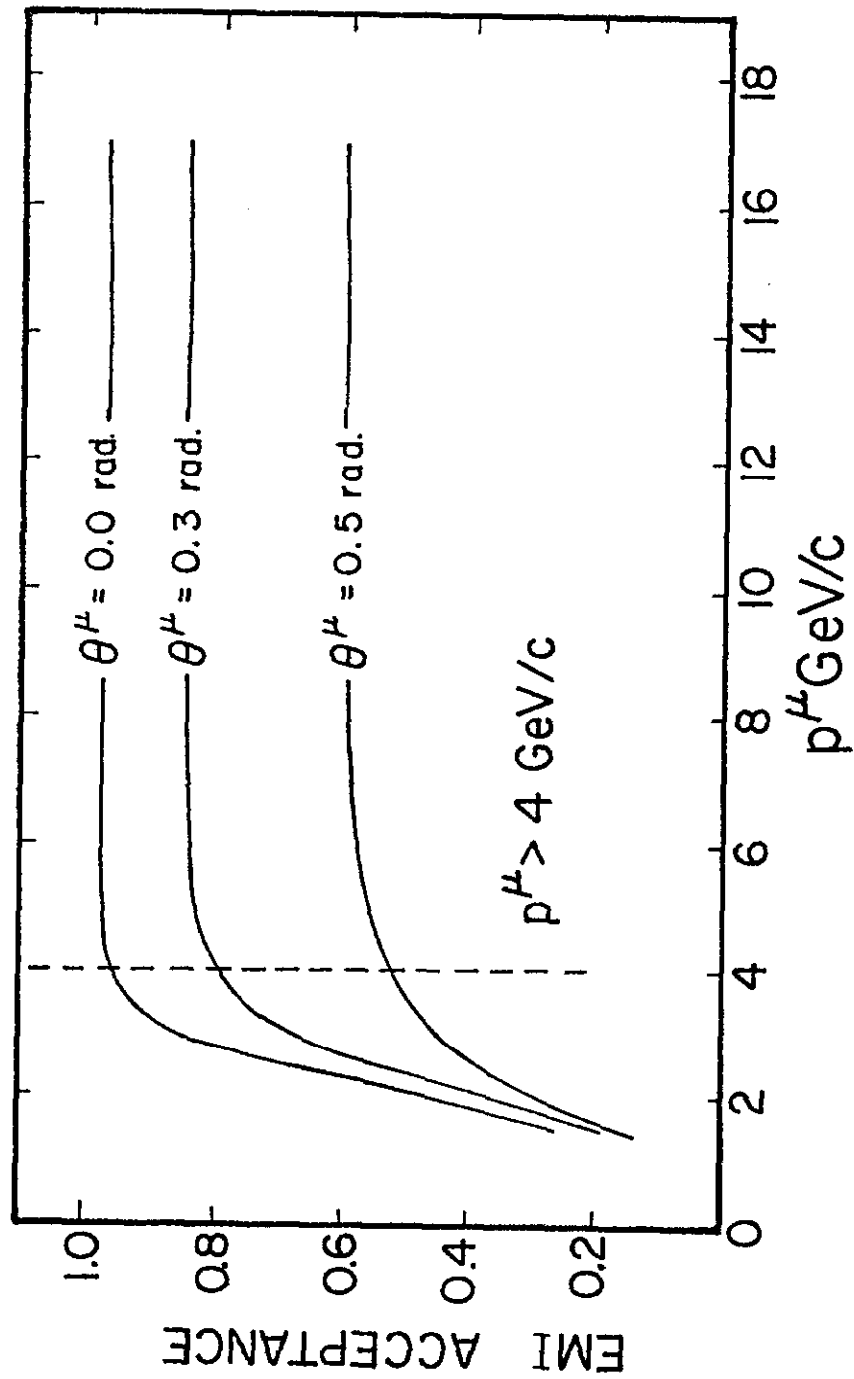


Fig. 1

